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Improved Exploration Potential in Shallow Gas-charged Channels through Constrained Data-driven Velocity Model Building and Imaging of 4-C Data: Case Study from Niger Delta Shallow Marine Environment

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Abstract Imaging of the shallow Pliocene channels in a legacy streamer 3D seismic dataset acquired in a Niger Delta shallow marine environment posed a serious challenge due to the presence of shallow gas-charged zones in the dataset, making the data sub-optimal for further exploration and field development. Acquisition of modern high quality 3D streamer data over the area was no longer feasible owing to dense facilities and field activities in the area. To maximize exploration potential especially of the deeper targets, a high density multicomponent seismic dataset was acquired over the area. Processing of the converted wave derived from the multicomponent data was very challenging due to the special binning requirement which relied heavily on the accuracy of the ratio of the compressional to converted wave velocities. This paper focuses on the velocity model building and imaging of the converted wave to adequately resolve the lateral inhomogeneities associated with the gas-charged channels. Comparison of the imaged result to the legacy data shows significant improvement in imaging over the gas zone with the converted wave data. The result is important for evaluation of the remaining exploration potential in the area and could also be useful in seismic reservoir characterization for field development. Constraining the velocity model building and imaging in the most efficient way to benefit the data-driven process is the main goal of this study.

Keywords: *converted wave, c wave, velocity model building, imaging, gas channel, Niger delta*

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1. Introduction

Like fault shadows, the presence of gas-charged channels pose a major challenge to subsurface imaging using conventional 3D seismic data. Conventional 3D streamer seismic acquisition is designed to acquire P-wave data which are affected by the presence of gas; compressional seismic velocities decrease in the presence of gas, and potential illumination over gas-charged channels could be significantly challenging as they cause velocity distortions and bright spots based on P-wave data. This is in addition to loss of amplitude and loss of higher frequencies in the presence of gas. This can be very frustrating in seismic reservoir characterization where it is desired to delineate as clearly as possible, the gas and water sand, and shale lithologies. Conventional seismic attributes are not optimum for detailed geometry description of channelized hydrocarbon bearing reservoirs in a deltaic system of deposition [1,2,3] such as in the current area of study. Converted waves are much less affected by gas [4]. These waves do not travel through fluids and as a result, they are mostly unchanged in the presence of gas.

3D 4-C seismic data acquisition involves measurement of the full 3D ground motion using a pair of sensors firmly planted on the ocean bottom, and an array of air guns which release pressure at some depths within the water column to constitute the source. The recording sensors comprise a vertical hydrophone designed to record the wavefield pressure, and a three-component geophone which records the vertical, horizontal and orthogonal components of the wavefield, respectively. Whereas the hydrophone and the vertical 3-C geophone are designed to target the compressional waves, the horizontal and orthogonal components are designed to target the converted waves (also referred to as shear waves), which constitute downgoing compressional waves that have become converted to upgoing shear waves at the deepest point of penetration. The converted waves are polarized in the fast and slow directions respectively.

A variety of rocks and fluids can have similar response to compressional waves whereas, the properties may well vary for S-waves [5], especially since the shear waves are mostly unaffected in the presence of formation fluids. On the other hand, some interface-based seismic interpretations may be defective in cases of low contrast in the P-wave recorded at such interfaces. For these reasons, compressional seismic alone may not be able to clearly delineate the subsurface in the presence of heterogeneities, and a combination of the P-waves and converted waves could produce products which could greatly aid mapping of the structure and type of rocks and fluids present in the subsurface. The multicomponent seismic data are processed separately for the P-wave and converted wave. Conventional P-wave processing routines may be adequate for the P-waves. Processing of converted seismic wave could be challenging because apart from conventional processing routines aimed at reducing noise and improving the signals, it also involves additional processes which are not normally performed on the P-wave data. For example, almost at the onset of the processing, the horizontal and orthogonal components of the wavefield are rotated in the radial and transverse directions, respectively. While subsequent processing is carried out on the radial component, the vertical component is discarded. This rotation arises from the fact that the emergence angle of the upgoing converted wave is normally higher than the angle of incidence of the downgoing P-wave and as a result, the point of mode conversion is not mid-way between the source and receiver, but dependent of the ratio of the P-wave to converted wave velocities. The ability to correctly define a bin location for the converted wave in reference to the source-receiver offset is therefore a big task in the processing of converted seismic wave. This binning process, also called asymptotic binning, relies on the correctness of the velocity ratio as incorrect value may result in poor imaging of the subsurface. Assuming a single layer, this is given by Eqn. (1), following [5].

$$X_a = \frac{X}{\left(1 + \frac{V_P}{V_S}\right)} \tag{1}$$

where,
X_a = offset of the conversion point from the receiver position, and
X = source-receive offset.

In view of the above, the major challenge in the processing of converted wave is the ability to build a velocity model capable of correctly imaging the subsurface in the presence of shallow heterogeneities. In this study, the exploration capability of converted seismic waves in imaging through gas-charged channels is demonstrated with emphasis placed on constraining the velocity model building and imaging to improve the imaging results.

2. Location and Geology of Study Area

The study area is located in the south eastern Niger Delta shallow marine. Average water depth in the area is about 20 m. The Niger Delta is composed of three (3) stratigraphic units namely the Benin, Agbada and Akata Formations. Whereas the Benin Formation comprises mainly continental fluviatile sands and gravels, the Agbada Formation, generally believed as the main reservoir unit, contains alternating sequence of sands and shales of coastal fluviomarine origin [6]. The Akata Formation forms the basal unit, and is made up mainly of marine shales with some stingers of sands. The Akata shales are at elevated temperatures and pressures, and are believed to be the main source rock in the Niger Delta. The three (3) Formations are distinctly present in the study area.

The depositional environment in the study area is mainly deltaic and pro-deltaic, with shoreface (lower and upper) and distributary channel facies forming the prevalent reservoir units. Structural style in the area includes a major NE-SW trending growth fault intersected by a series of smaller growth faults and rollover systems, forming antithetic faults with associated anticlinal traps.

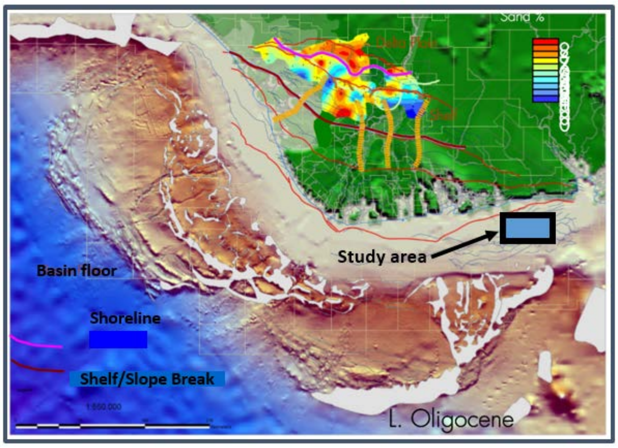

Figure 1. Map of the Niger Delta showing the study area

3. Materials and Methods

3.1. Materials

Data used for this study comprise 3D 4-C OBC seismic data acquired over an area of about 250 km^2 in the shallow marine environment of south eastern part of the Niger Delta. The data were acquired with a flip flop shot spacing of 25 m and a pair of receivers spaced 25 m and oriented at 90°/270°. The energy source was an array of a pair of G-guns laid at an average water depth of 5 m. The data had been processed to generate separate PP and PS volumes that tied the legacy PP volume.

3.2. PP Velocity Model Building

Data-driven RMS velocities were manually picked on denoised PP CMP gathers using semblance-based velocity analysis over a series of test lines on a 1 km x 1 km grid (Figure 2). The resulting velocity field was converted to interval velocity field, smoothed and used to generate Kirchhoff pre-stack time migration on selected target lines. Five iterations of the velocity model building were carried out. Each iteration involved updating the velocity model by minimizing the residual moveout in order to obtain further flattening of the migrated gathers and re-migration.

CMP gathers produced from pre stack time migration with the final model showed insignificant residual moveout. The final velocity model was thus used to generate a curved-ray Kirchhoff full volume pre-stack time migration to create a structural stack of the PP volume, on which horizon interpretations were carried out.

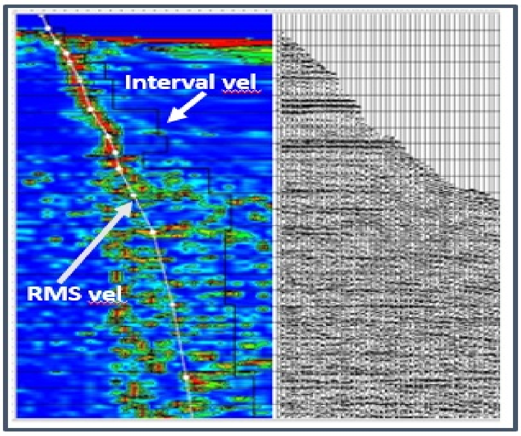

Figure 2. RMS velocity analysis

3.3. PS Velocity Model Building

A different approach was used to constrain the velocity model for the converted wave. In the first place, the denoised C wave data was split into positive and negative offsets. An initial C wave NMO velocity field was then built by extrapolating NMO velocity function picked from the data, which was thereafter applied to re-migrate the data, updating the velocity model in the process by reducing the residual. The process was repeated until a final C wave NMO velocity field, γ_n, was obtained. This final velocity was used to create a structural stack of the C wave data. The process was done for both the positive and negative offset datasets. The same horizons interpreted on the PP volume were then interpreted on the PS volume to generate the initial vertical velocity ratio values, known as Gamma zero values, defined by:

$$\gamma_0 = \frac{V_{P0}}{V_{S0}} = \frac{t_{S0}}{t_{P0}} \qquad (2)$$

where t_{S0} and t_{P0} are one-way travel time to the respective interpreted horizons from the ocean bottom. Correlating events on the PP and PS volumes is a very important step which requires great care, as inaccurate correlation often leads to erroneous interpretation of the velocity ratio and other seismic-based attribute interpretations.

Using the Gamma zero field, the data was re-migrated to obtain an updated Gamma zero field on the two C wave offset volumes. The positive and negative re-migrated offset volumes were then correlated to obtain a single function effective Gamma, defined as:

$$\gamma_{eff} = \frac{{\gamma_n}^2}{\gamma_0} \qquad (3)$$

where γ_n is the stacking velocity (i.e., updated C wave NMO velocity field) and γ_0 the updated Gamma zero field. The procedure above was also repeated to refine the effective Gamma volume. Using the constrained stacking velocity (C wave NMO), vertical velocity ratio (γ_0) and effective velocity ratio (γ_{eff}) fields, a Kirchhoff pre-stack time migration was carried out to obtain the final PP-PS image (converted wave image).

4. Results and Discussion

Figure 3 and Figure 4 show results of the constrained respective stacking velocity models for the P wave RMS and C wave NMO fields which provided the best overall flattening of the migrated gathers spatially over the survey area as a result of the significant reduction in residual moveout achieved with the final iterations of the velocity model building. The purpose of constraining the velocity models through iterations was to simulate a real case geologic scenario to include velocity distortions resulting from subsurface heterogeneities interplaying in the data since the geologic model in actual field situation is not known but assumed. Figure 5 shows horizon interpretations on migrated P wave and C wave structural stack sections. Seven (7) horizons have been interpreted on both volumes to derive the single function vertical velocity ratio values. Figure 6 shows the Gamma zero single function, interpolated Gamma zero and the final Gamma zero models.

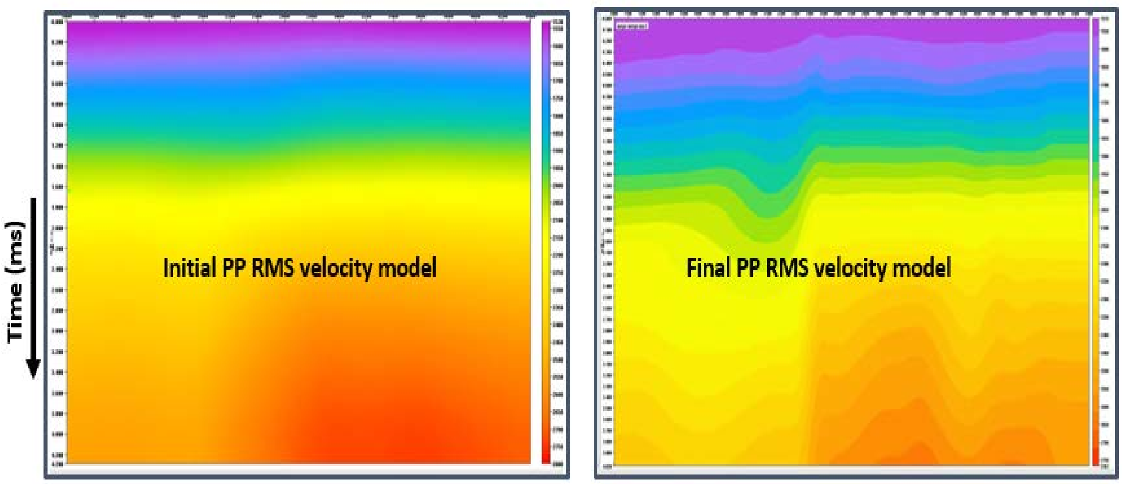

Figure 3. Initial and final P wave stacking velocity models. The initial Model is smoothed RMS velocity field derived from velocity analysis

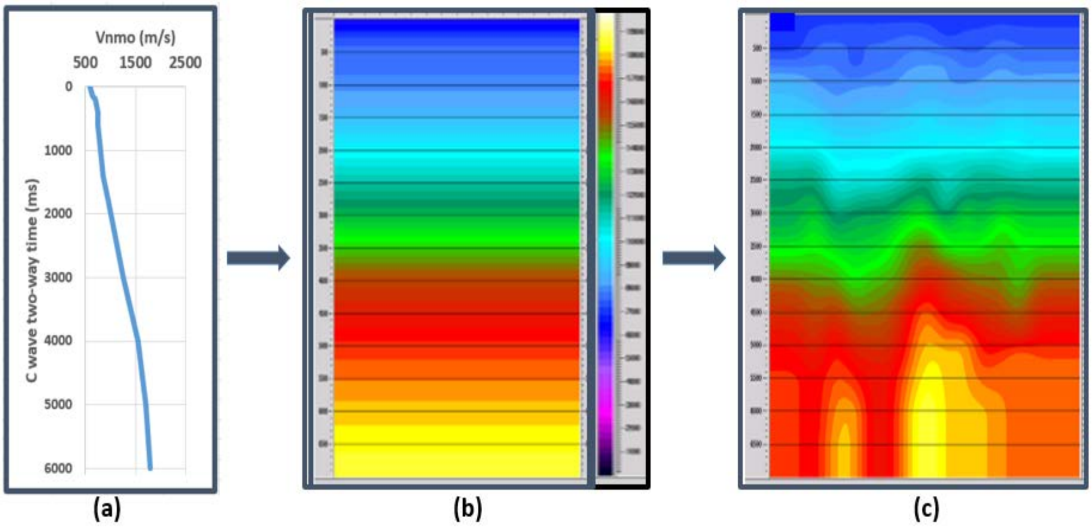

Figure 4. C wave single NMO velocity function (a), interpolated NMO (b) and final NMO velocity models (c)

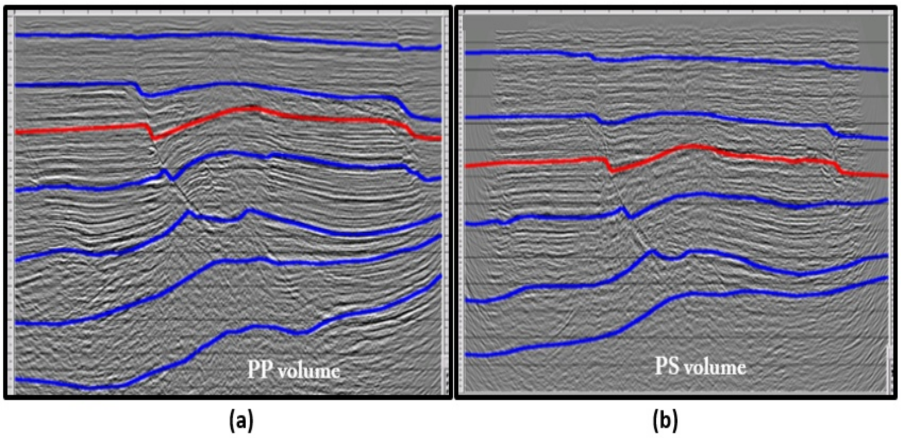

Figure 5. P wave (a) and C wave (b) structural stacks with interpreted horizons for velocity ratio derivation

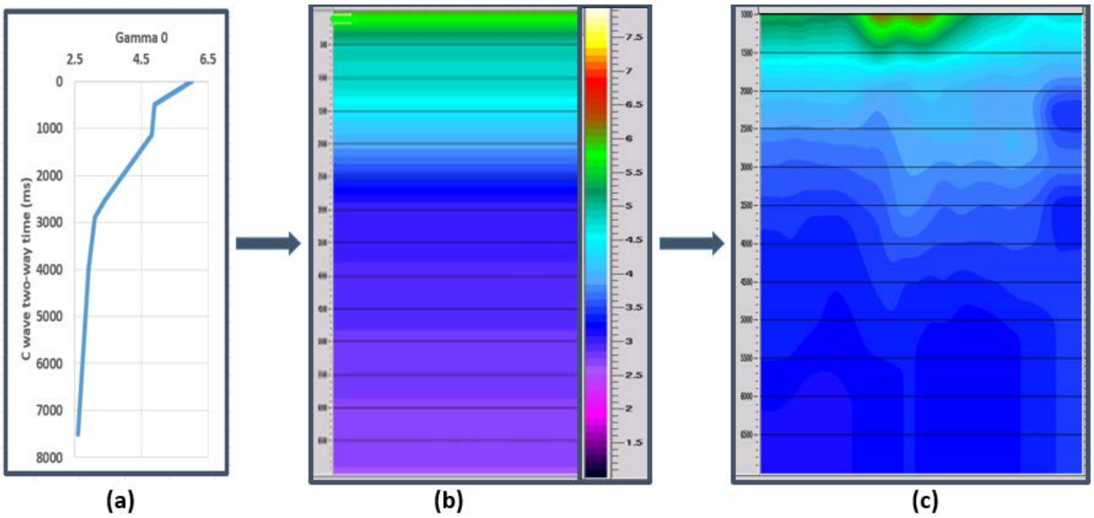

Figure 6. C wave single Gamma zero function (a), interpolated Gamma zero (b) and final Gamma zero model

Figure 7 shows the Kirchhoff pre stack time migration structural stack volume from the fully processed legacy streamer data over a section of the survey most affected by the shallow gas channels. The gas-charged zone has been identified on the basis of the significantly reduced P wave amplitude across the zone suggestive of the presence of gas. Post migration processes such as residual moveout correction, residual multiple attenuation, time variant filter and residual true amplitude recovery have been applied to this volume to improve structural definition, signal to noise ratio and balance the section temporally. Even with these processes, the presence of gas shadows in the final image is clearly evident in the data. The poor imaging in the gas-charged zone may have been the result of significant attenuation of high frequency component and scattering of the P-wave energy, causing a reduction in its velocity as it propagates through the gas charged channels. Antithetic faults resulting from a major NE-SW trending growth fault intersected by a series of smaller growth faults and the associated rollovers (Figure 8) are prevalent in the study area [7]. The shallow gas may have been trapped behind these complex fault systems or may have been leaked from deeper reservoirs and become trapped in the area. Although the gas-charged channels and the dimming of the P-wave amplitudes occur in the shallow, near-surface, imaging in the deeper reservoirs with the P wave would have also been affected as a result of the high frequency attenuation and scattering that have taken place in the shallow gas-charged zone. Reservoir characterization based on the P wave data would be generally affected, especially in the shallow zone.

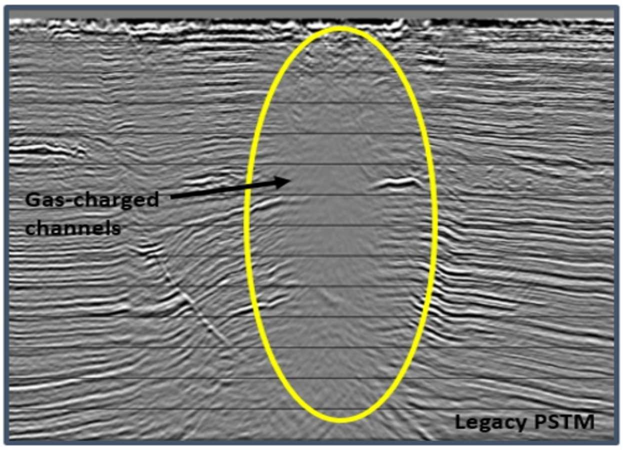

Figure 7. Legacy fully processed Kirchhoff PSTM image over a section of the survey area. The poorly imaged section indicates the shallow gas-charged zone

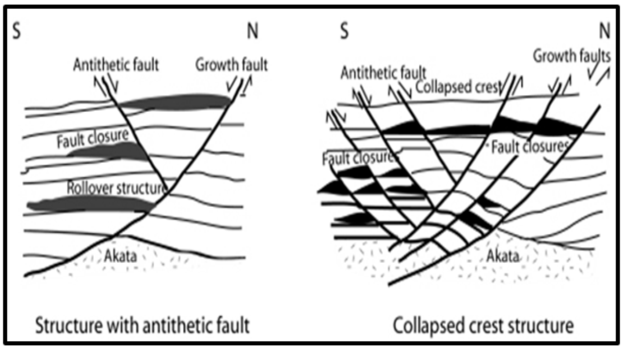

Figure 8. Typical fault and trap systems prevalent in the Niger Delta area of study (modified from [7], and [8]

Figure 9 shows the raw Kirchhoff pre stack time migration structural stack volume from the C wave data for the same area of the survey. Even though further post migration processes were yet to be applied, the result shows a significant imaging through the gas channels compared to the legacy data. C waves are less sensitive to formation fluids; they could propagate through gas channels significantly unaffected and as a result, they could illuminate gas-induced subsurface heterogeneities with a properly constrained velocity model and imaging. Detailed structural and stratigraphic interpretations in the final processed C wave volume would be beneficial for reservoir characterization and greatly improve exploration potential in the area.

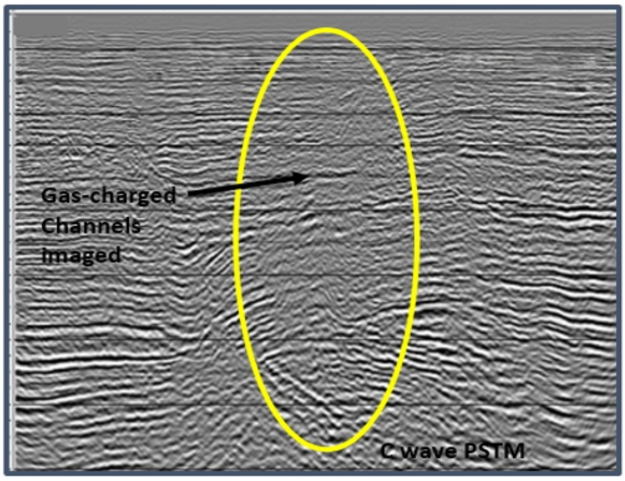

Figure 9. Raw C wave Kirchhoff PSTM image over the same area in Figure 7, for comparison. The shallow gas channels are significantly illuminated in this image. Post migration processing will further illuminate the image and real clearer event continuity

5. Conclusion

P-wave seismic data have been shown in this study to be inadequate in resolving near-surface heterogeneities to image gas-charged channels causing the heterogeneities. This could be attributed to attenuation of high frequency signals and scattering of the P wave energy in the gas zone, which might have resulted in slowing down of the P wave velocity in the gas. By deploying a data-driven, well-constrained velocity model building and imaging using converted wave, the gas–zone was sufficiently imaged to improve exploration potential in the area. Converted waves are known to be less sensitive to fluids, but building a reasonable velocity model to image gas charged zone with C wave data could be quite challenging due to difficulty in the determination of velocity ratio. The data-driven methodology adopted for this work simulates actual field geologic scenario by incorporating data-derived model of velocity distortions caused by presence of the gas channels, giving further credence to the final imaged result. In addition to improvement in the exploration potential, the C wave image could be useful for regional reservoir characterization that could lead to identification of by-passed plays.

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